Testing for Dark Matter Trapped in the Solar System

Timothy P. Krisher[a]

[a]Jet Propulsion Laboratory,
4800 Oak Grove Drive, Pasadena, California 91109

We consider the possibility of dark matter trapped in the solar system in bound solar orbits. If there exist mechanisms for dissipating excess kinetic energy by an amount sufficient for generating bound solar orbits, then trapping of galactic dark matter might have taken place during formation of the solar system, or could be an ongoing process. Possible locations for accumulation of trapped dark matter are orbital resonances with the planets or regions in the outer solar system. It is possible to test for the presence of unseen matter by detecting its gravitational effects. Current results for dynamical limits obtained from analyses of planetary ephemeris data and spacecraft tracking data are presented. Possible future improvements are discussed.

1. INTRODUCTION

Dark, or unseen, matter in the solar system could reveal its presence through detectable gravitational effects. The gravitational field of an unseen distribution of matter or of an individual body could measurably perturb the orbits of the known planets. Well-observed comets (e.g., P/Halley) can also be used to detect gravitational perturbations. The motion of a deep space probe can be determined to an interesting level of accuracy by precisely measuring the Doppler shift of radio transmissions to and from the spacecraft. Its distance can also be accurately determined by measuring the propagation time of a radio ranging signal. in this paper, we will briefly review dark matter issues in the solar system, dynamial tests, and a promising new method that consists of detecting the gravitational redshift with a space probe.

Beginning in the next Section, reasons are given for why we might expect to find unseen matter in bound solar orbits, and where we would most expect to find these orbits. Dark matter candidates having the most likelihood of being present in the solar system at concentrations that could produce detectable gravitational effects will be discussed, where both nonbaryonic and conventional forms of matter are considered. Motivating reasons, arguments for and against, and even evidence of certain candidates, will be given. In Section 3, dynamical tests are discussed, and results obtained from them up to now are summarized. The proposed gravitational redshift test is described in Section 4. Concluding remarks appear in Section 5. Because of publication constraints on the number of pages allowed for this paper, the References are strongly recommended for further details on the topics that follow.

2. DARK MATTER. IN THE SOLAR SYSTEM

2.1. Orbit Trapping

Given that there might exist a cosmological or galactic background of dark matter [1], then we would expect a flux of material into the solar system at a rate dependent upon the density of material and relative velocities. Material could become trapped into bound solar orbits, provided that excess kinetic energy can be removed. Limits on the flux of extra-solar dust, comets, or meteoroids have been discussed by Hills [2]. Collision of such objects with the Sun or a planet could lead to orbit trapping of residue or debris. Certain unconventional candidates that are dense and massive enough could pass completely through the Sun or a planet and loose enough energy to become bound into orbit. Examples of candidates that could accomplish this feat are primordial black holes [3] or strange quark nuggets [4,5]. Nonbaryonic particles that interact only weakly with normal matter (e.g., Weakly interacting Massive Particles [WIMPs] [6]) could also become trapped by this process. The question is whether dark matter could become concentrated in certain orbits at appreciable levels above the background. In the inner solar system, gravitational scattering by Jupiter and the inner planets is expected to prevent concentration of weakly interacting particles above background levels duc to a process of gravitational diffusion [7].

Dark matter could have been brought into the solar system during its initial stages of formation. Molecular clouds in the galaxy are known to be sites of active star formation [8]. The gravitational collapse of the early solar nebula could assist in concentrating dark matter along with normal matter in the cloud. This *process* was considered for the case of heavy neutrinos, with promising results initially [9]. It was shown that the neutrinos could undergo dissipationless collapse and violent relaxation with normal matter. For dissipative collapse, although the neutrinos would be left behind, it was argued that their density would still be enhanced. However, it was later *shown* that this conclusion was erroneous and that enhancement would not occur [1 O]. Other forms of dark matter have been proposed that could undergo significant dissipation and become concentrated in the solar system; these are discussed further below.

Trapped particles or objects could persist in certain orbits for long periods of time at resonance locations (see [1 1] and references therein), although not necessarily indefinitely [12, 13]. For example, the asteroid belt population increases as we move inward from Jupiter, rising dramatically within half-way the distance to Marx (see Fig. 3 of Ref. [13]). This corresponds to a 2:1 resonance. Significant vacancies appear at higher resonances (the famous Kirkwood Gaps). Despite substantial clearing; near Jupiter, there are populated regions at the stable Lagrange points (Trojan asteroids) and at a 3:2 resonance (Hilda group). In the outer solar system, for example, Pluto is in an interesting 3:2 resonance with Neptune [14]. Numerical studies have demonstrated long orbital lifetimes (of order 100 million yrs and greater) starting beyond Neptune (see Fig. 2 of Ref. [15]), suggesting the outer solar system as a promising place to probe for surviving dark matter.

2.2. Nonbaryonic Candidates

In addition to weakly interacting particles, such as WIMPs, more strongly interacting types of particles have been proposed, such as CHArged Massive Particles (CHAMPs) [16] and Strongly Interacting Massive Particles (SIMPs) [1 7]. These particles have a number of potentially observable effects in the solar system, which are discussed in the preceding references. However, a significant astrophysics constraint is set by the argument that they would accumulate in a neutron star and convert it to a black hole [18]. Magnetic monopoles are another possibility. Meteorites have been analyzed to search for monopoles possibly embedded in them [19]. Strange quark nuggets or primordial black holes could become trapped in the solar system, as mentioned above, but, again, astrophysical constraints, as well as cosmological production considerations, would seem to limit anticipated abundances severely. Another interesting possibility is "shadow matter", which would interact only gravitationally with normal matter [20]. However, this very property would most likely lead to segregation of the two forms of matter in the galaxy.

Rather than particles becoming trapped in the solar system, the solar system could be embedded in a bound system, or cloud, of particles. For example, a "neutrinosphere" has been proposed, in which massless relic neutrinos are bound together by exchange of a scalar boson [21]. In order for this neutrino background to explain the low-energy tail in tritium β-decay experiments on the earth, their total number would need to have a maw of $10^{-7}\,M_{\odot}$ within the orbit of Jupiter. Bonding interactions between WIMPs have also been considered by others [22].

2.3. Conventional Candidates

In addition to the known planets, asteroids, and periodic comets (for a survey, see Reference [23]), other bodies or populations of objects have been proposed to exist in the outer solar system.

Residual matter could be left there from the early stages of solar system formation [24,25], possibly after having been scattered out of the inner solar system [26]. In the outermost region, the Oort cloud of cornets would provide the source of observed long-period comets ($P > 200$ yrs) [27]. It could contain nearly 10^{13} comets in a spherical shell between 10^4- 10^5 AU. The total mass could be between 10 – $10^3 M_{\oplus}$, depending upon the size distribution and physical density of the bodies. Starting just beyond the orbit of Neptune, the Kuiper belt of comets could contain roughly 10^9 comets, with a total mass of 0.3 $M_{\oplus}$ (or possibly higher) [28]. Possible Kuiper belt members have now been observed mar the anticipated location. Ground-based observations have revealed objects with diameters estimated to be of order 100 km [29], while objects only 10 km in size have been found with Hubble Space Telescope [30].

Larger planetesimals could remain from the early history of the solar system. A class of Pluto-size objects has been proposed [31], based upon circumstantial evidence for possible collision scenarios involving such objects and Uranus, Neptune, and Pluto. Originally, they would have numbered between 10^2– 10^4. Certain analyses of observations of the orbits of Uranus and Neptune have been interpreted to imply the influence of a tenth planet, known as Planet X. The masses proposed for it range between 0.5- 5 $M_{\oplus}$. However, a reevaluation of the available data and 'its analysis disputes apparent evidence for Planet X at present [32]. Cosmogonical arguments can also be made for its unlikely formation [33]. A solar companion star has also been proposed of 0.1 $M_{\odot}$ in an orbit with a semimajor axis of 10^5 AU (see Ref. [34] for further discussion of this idea, and more generally on the topic of solar system dark matter).

3. DYNAMICAL TESTS

In this section, wc will review dynamical tests that can be performed to detect unseen matter in the solar system. These tests rely on observing the motion of known natural bodies, or by using techniques to track the motion of a spacecraft. Each method has certain merits, as well as limitations.

3.1. Observing Natural Bodies

Observations of the positions of the known planets can be fit by least-squares to a model for the solar system [35 37]. An effort is made to make the model as complete and accurate as possible, which includes modeling gravitational perturbations from hundreds of known asteroids [37]. Any remaining deficiencies in the model, such as due to unseen gravitating mass, would be apparent from nongaussian residuals after the fit, or by an inability of the resulting ephemerides to make correct predictions in the future. This method of detecting unseen matter and its present capabilities has been nicely reviewed in Reference [38]. Its sensitivity depends upon the number and accuracy of the observations. Highly accurate, direct measurement of the distance to a planet by radio ranging to a space probe has provided the greatest improvement in sensitivity. Limits obtained as of 1989 on unseen mass assumed to be spherically distributed interior to the orbit of a planet have been compiled in 'Table I of Reference [34], where results obtained up to Uranus were included. An analysis that includes ranging data obtained with the Voyager 2 spacecraft during its flyby of Neptune has since been completed [39], yielding a limit of (-2.0 ± 1.8) x $10^{-6} M_{\odot}$ at that distance from the least-squares fit that was done. We can only speculate at this point whether the negative sign is suggestive of attraction from additional mass beyond. The assumption of a spherically symmetric distribution in these analyses greatly simplified the computer modeling; more specific models remain to be thoroughly tested (e.g., a belt of material). Limits that could be obtained on the mass of the Kuiper belt have been discussed in Reference [38]. A limit of roughly 0.3 $M_{\oplus}$ has been derived from observations of comet P/Halley, but must be treated cautiously.

3.2. Spacecraft Tracking

Deep space probes, such as Pioneer and Voyager, can be tracked to large distances in the solar system, and to high precision, with the large radio antennas of the NASA Deep Space Network (DSN). Pioneer is the most useful for testing for dynamical perturbations from unseen mass, the reason being that it is spin-stabilized. Because the Voyager spacecraft is three-axis stabilized, necessary attitude control maneuvers limit its usefulness as a dynamical probe. Over time, small residual translational acceleration errors could accumulate, masking the sought-after gravitational signatures from unseen mass. In either case, a variety of other non-gravitational acceleration sources also must be accounted for accurately, the list including solar radiation pressure, photon-thrust from the spacecraft transmitted radio signal, or anisotropic thermal emission. There also exists a potential threat from thruster leaks too small to be detected by on-board sensors.

Boss and l'talc considered the effect of the mass of a ring of cometary bodies on the Pioneer [40], assuming a limiting sensitivity of 10^{-11} km/s^2 in 1975. By 1984, as the spacecraft approached a distance of 35 AU, it was concluded from further analyses that Pioneer acceleration errors did not exceed 5 x 10^{-14} kill/s^2 over 6 month integration intervals [41]. This provides a limit of 5 $M_\oplus$ fora ring assumed to lie between 35- 56 AU, subject to the caveats in the preceding paragraph. The gravitational tug from individual bodies that the Pioneer might pass can also be tested. Pluto-sized objects would be detectable at a flyby distance of 0.3 AU for the limiting sensitivity quoted (see Ref. [31]). Both spacecraft continued to provide useful Doppler data until the receiver on Pioneer 11 ceased to function in October 1990. Doppler data was still being provided by Pioneer 10 after that point. At a rate of 2.3 AU/yr, it will have reached a distance of greater than 70 AU from the Sun by the year 2000.

4. A PROPOSED NEW TEST

A spacecraft equipped with a stable frequency standard could be used to measure the gravitational redshift produced by unseen mass, as proposed in Reference [42]. For a coherently transponded radio signal, the gravitational red(blue)shift shift cancels out in the signal received back on the ground, whereas the Doppler shift from the velocity is multiplied by a factor of two. By differencing the measured frequency of a signal transmitted directly from the spacecraft and one-half that of a transponder signal, non-gravitational errors in the Doppler shift can be removed to first order in the velocity. The gravitational redshift could then be tested with a sensitivity that is limited mainly by the stability of the on-board frequency standard. Certain atomic frequency standards potentially could have enough long-term stability to permit this technique to meet or exceed the sensitivity of conventional Doppler tracking. Trapped-ion standards are now being built and tested at J]'], that could meet the required stability, as well as satisfy low-mass and low-power constraints for use on a spacecraft.

5. CONCLUSIONS

We have discussed possible forms of dark matter that could be trapped in solar system orbits and trots for their gravitational effects. Candidates from a galactic or cosmological background might reach detectable levels, but a dissipation or interaction mechanism is required for them to concentrate with sufficient total mass. At the same time, sue}] models would have to avoid potentially more stringent astrophysics constraints. The outer solar system starting beyond Neptune appears to be the most promising place to find substantial amounts of material persisting in bound orbits for up to the age of the solar system. Dynamical tests using the planets, comets, and deep space probes have provided some limits up to now. Testing for gravitational redshifts with a deep space probe could substantially augment testing for dynamical effects, and with future atomic frequency standards potentially could have even greater sensitivity to unseen mass.

6. ACKNOWLEDGEMENTS

We thank J. D. Anderson for sponsoring and encouraging the research presented here, as well as for discussions. Our thanks also go to 1). C. Rosenbaum and V. I,. Teplitz for inspiration and discussions, and to A. Gould for helpful comments. This work was performed at the Jet l'repulsion Laboratory of the California institute of Technology, which is under contract to the National Aeronautics and Space Administration.

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